Transient Response of a Turbocharger

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Abstract

Turbochargers are used to increase the boost power of any IC engine without compromising the size of the engine. While using Turbochargers, the transient response of the engine can become worse because the Turbocharger's compressor is not physically connected with the engine hence not derived by engine and solely depends on the exhaust gases produced by the engine, so it is important to study the transient response of the engine to counter this problem.

This thesis provides the method used to study the transient response of the Turbocharger under conditions. We used BorgWarner Turbo speed sensor, Toyota MAP Sensors and K-Type EGT Thermocouples and acquired data from these sensors with the help of NI equipment using Labview software.

Key Words: *IC engine, turbocharger, transient response, boost power*

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ABBREVIATIONS

MAP	Manifold Absolute Pressure
EGT	Exhaust Gas Temperature
IC	Internal Combustion
RPM	Revolutions per minute
DAQ	Data Acquisition
NI	National Instrument
MOI	Moment of Inertia
mm	Millimeter
cc	Cubic centimeters
V	Voltage
hp	Horse power
G	Ground
AFR	Air to Fuel ratio
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
ECU	Electronic Control Unit

CHAPTER 1: INTRODUCTION

The research work in this thesis is related to Internal combustion Engines, its boost power, efficiency and controlling the emissions released by the engines. Turbocharger is used to increase boost power and improving the efficiency of engine without downsizing the engine.

1.1 Background, Scope and Motivation

Turbocharger is a device which is used to re-use the exhaust gases of an engine. It has two important components which are turbine and compressor. The exhaust gases helps to run the turbine which with the help of shaft is connected with compressor rotor and compressor also moves along with the turbine rotor. In modern era, it is highly demanded that the vehicles should be efficient without downgrading their engine, so turbocharger plays an important role in fulfilling that demand. It is used in diesel powered cars, gasoline powered cars, aircrafts and ships. It can also be used for industrial applications to make the generators efficient.

A turbocharger has a compressor rotor, turbine rotor, shaft connecting compressor and turbine, waste-gate for regulating the gases entering the exhaust side turbine and eventually to the manifold through the intake. Water injection is also used to control the temperature of the intake air.

The Turbocharger which we choose for our research is RHB31 Turbocharger by IHI mounted on a 660cc gasoline powered test bench.

1.1.1 Some Basics about Engines

An engine is a device which is used to convert any form of energy to mechanical energy. Like electric motor converts electrical energy to mechanical energy. Engines/motors minimized the human work and also saves time in doing some kind of work. The first automobile engine was invented by Flemish Jesuit in 1678. There are two types of engines:

1. **Internal Combustion Engine**: This is the type of engine in which the combustion takes places inside the engine i-e cylinder. The most commonly used IC engines are automobile gasoline and diesel powered engines. The very first IC Engine was created by Etienne Lenoir in 1859 which was used for the commercial purpose. In 1876, Nikolaus OTTO created the first modern IC Engine. With the passage of time, more changes were made to improve the engine for the better use.

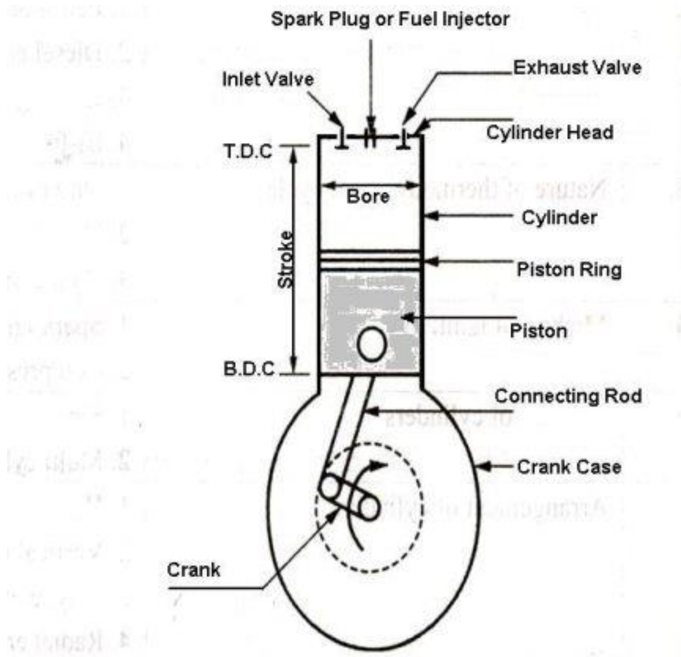


Figure 1.1: Internal Combustion Engine (https://www.theengineerspost.com/internal-combustion-engines-i-c-engines/)

2. **External Combustion Engine**: The type of engine in which the combustion takes place outside the engine. The first External Combustion engine was invented by Robert Stirling in 1816 having the highest efficiency by a practical engine. However, In 1823 Nicholas Carnot invented the highest efficient theoretical engine. The most commonly used EC engines are steam engine.

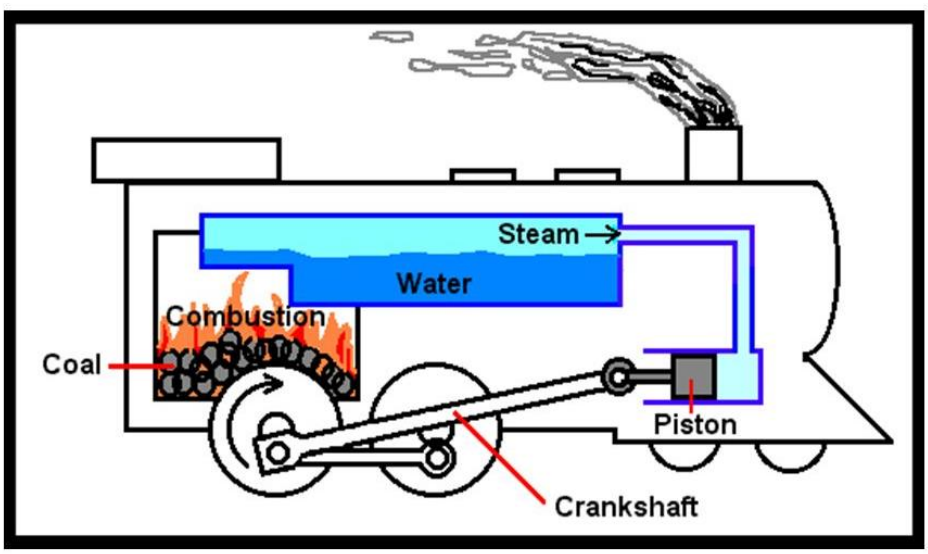


Figure 1.2: External Combustion Engine (http://luisgreatshop2707.mx.tl/external-combustion-engine-diagram.html)

1.1.2 Classification of Engines

1.1.2.1 With respect to Design

The types of engines with respect to their designs are:

1. **Rotary Engine**: It is a type of engine in which the power is obtained by the rotary motion of rotor of the engine which is present inside the chamber. Turbine engines are example of rotary engine.

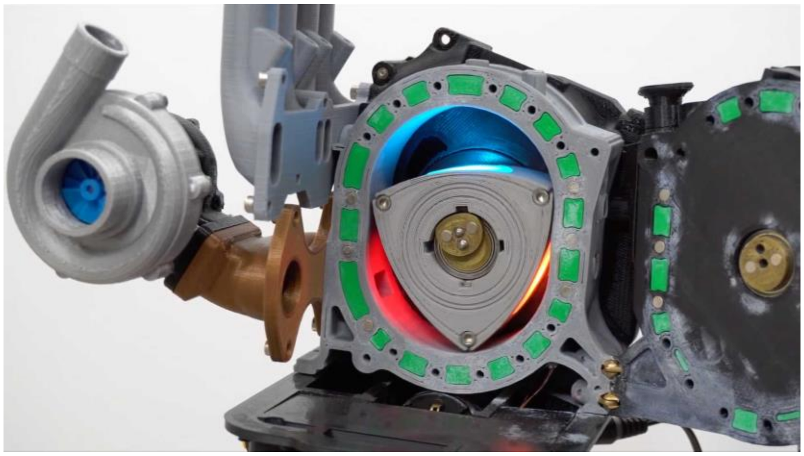


Figure 1.3: Rotary Engine (https://www.motor1.com/photos/644797/3dprinted-mazda-rotary-engine/)

2. **Reciprocating Engine**: It is a type of engine in which we have a cylinder and a piston which moves To and Fro within the cylinder. It is called reciprocating due to this motion. Four and two strokes engines are example of this type of engine.

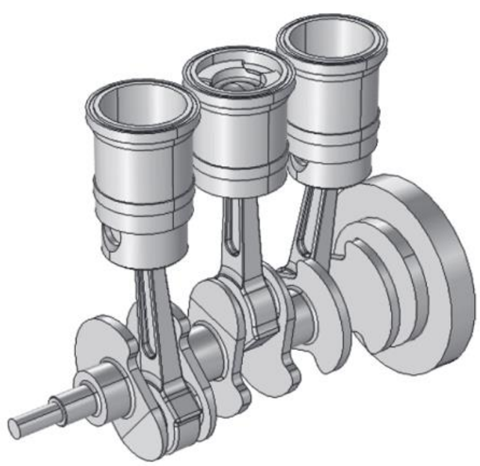


Figure 1.4: Reciprocating Engine (https://www.comsol.com/blogs/improving-the-operational-lifetime-of-a-reciprocating-engine/)

1.1.2.2 With respect to Fuel

The types of engine with respect to fuel usage are:

1. Gasoline Engine
2. Diesel Engine
3. Compressed Natural Gas (CNG) Engine

1.1.2.3 With respect to Operating Cycle

The type of engine with respect to operating cycle used in engine are:

1. **Otto Cycle Engine**: The engine that works on the principle of Otto Cycle is known as otto cycle engine. Otto cycle is composed of four thermodynamic processes which are cyclic and can be repeated for an infinite period of time. The processes are:
    a. Intake
    b. Compression
    c. Power
    d. Exhaust

Table 1.1: Otto Cycle

OTTO Cycle	
Process 0-1	Intake Stroke
Process 1-2	Compression Stroke
Process 2-3	Ignition Phase
Process 3-4	Expansion Stroke
Process 4-1	Heat Rejection
Process 1-0	Exhaust Stroke

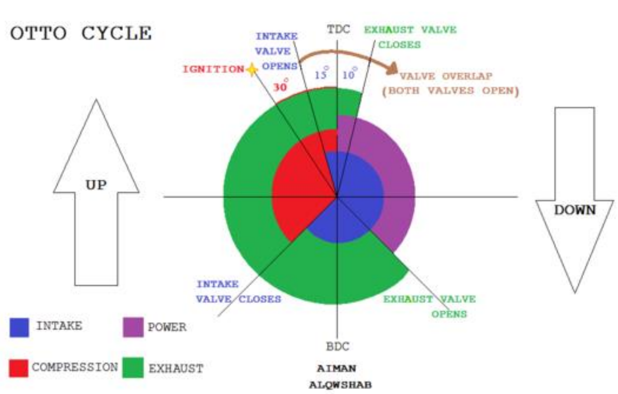


Figure 1.5: Thermodynamic Processes of OTTO Cycle (https://www.wikiwand.com/en/Otto_cycle)

Otto Cycle consists of an Isentropic (No heat lost or gain) compression (1-2) and expansion (3-4) and heat rejection (4-1) and addition at a constant volume (2-3) as shown in figure 1.2.

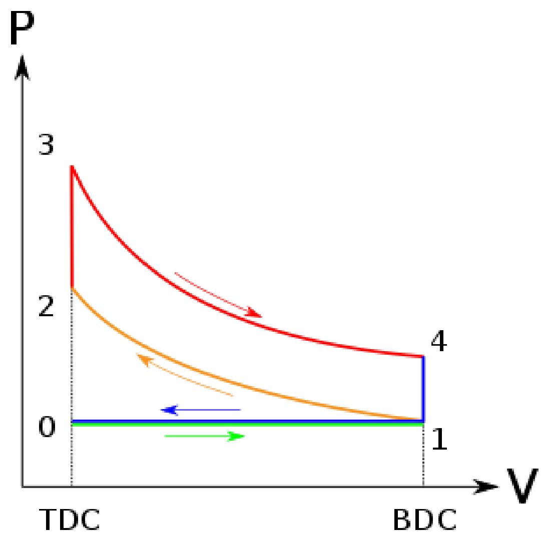


Figure 1.6: Cyclic process of Otto Cycle (https://en.wikipedia.org/wiki/Otto_cycle)

2. **Diesel Cycle Engine**: The engine that works on the principle of Diesel Cycle is known as diesel cycle engine. It also has four thermodynamic processes. It is similar to the Otto cycle except for one process, it has one isobaric process (Constant Pressure) instead of Isochoric (Constant Volume).

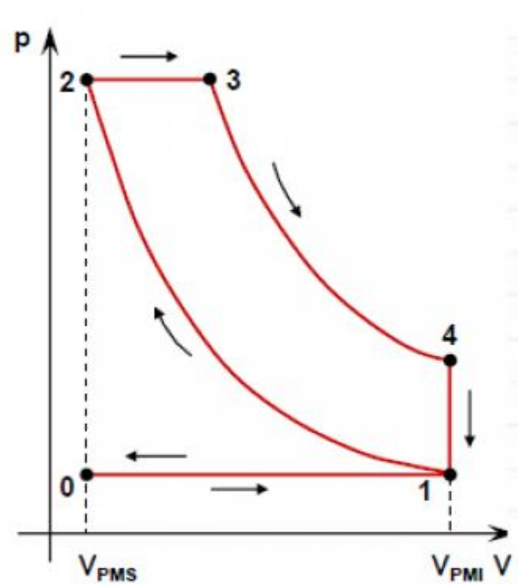


Figure 1.7: Cyclic process of Diesel Cycle (https://en.demotor.net/heat-engine/diesel-engine/theoretical-diesel-cycle)

3. **Dual Cycle Engine**: The engine that works on the combination of both Otto and Diesel cycle is known as dual cycle engine. It has two isentropic processes, two isochoric processes and an isobaric process.

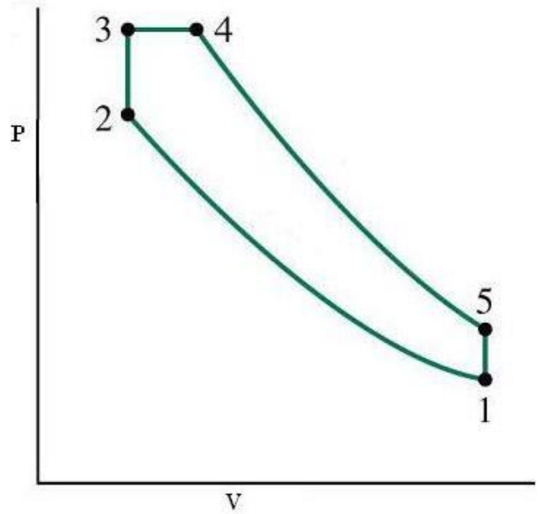


Figure 1.8: Cyclic process of dual cycle (https://www.brighthubengineering.com/marine-engines-machinery/9605-theoretical-cycles-in-marine-diesel-engines-the-dual-cycle/)

1.1.2.4 With respect to number of strokes

The type of engine with respect to number of strokes used in engine are:

1. **Two Stroke Engine**: The type of engine in which the piston moves two times from BDC to TDC and vice versa in one complete cycle.

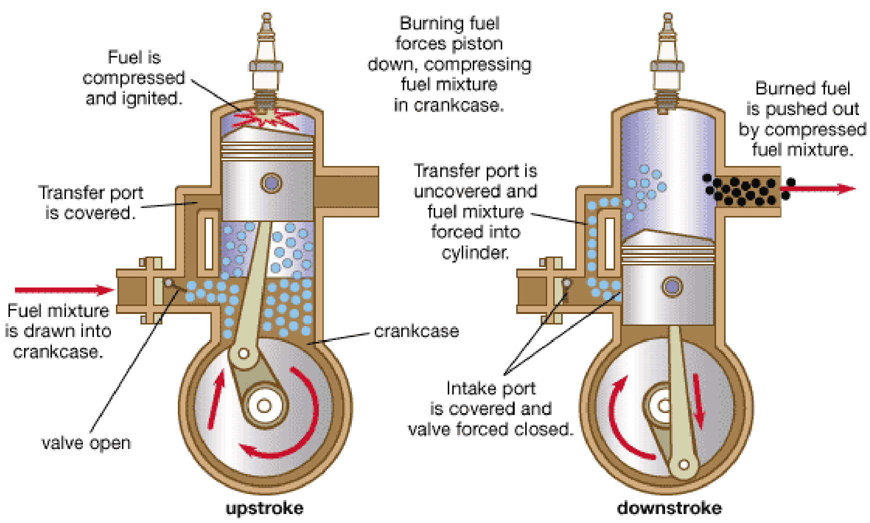


Figure 1.9: Two Stroke Engine (http://auto-diesel.blogspot.com/2012/05/2-stroke-cycle-petrol-engine.html)

2. **Four Stroke Engine**: The type of engine in which the piston moves four times. Two times from BDC to TDC and two times from TDC to BDC in one cycle. We get power after 720 degrees.

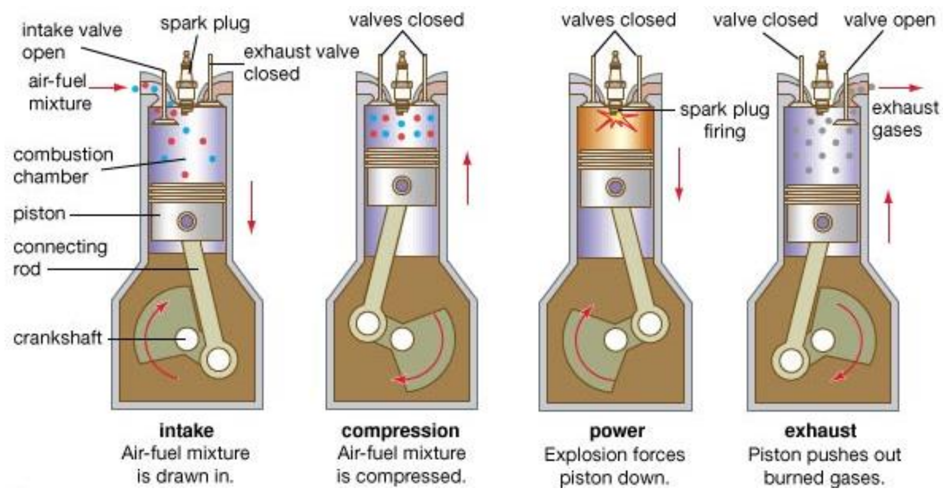


Figure 1.10: Four Stroke Engine (https://www.thinglink.com/scene/439722225466081280)

1.1.2.5 With respect to type of ignition

The type of engine with respect to type of ignition in engine are:

1. **Spark Ignition Engine**: The fuel is ignited with the help of spark plug fitted at the head of engine. Common example are petrol engines.

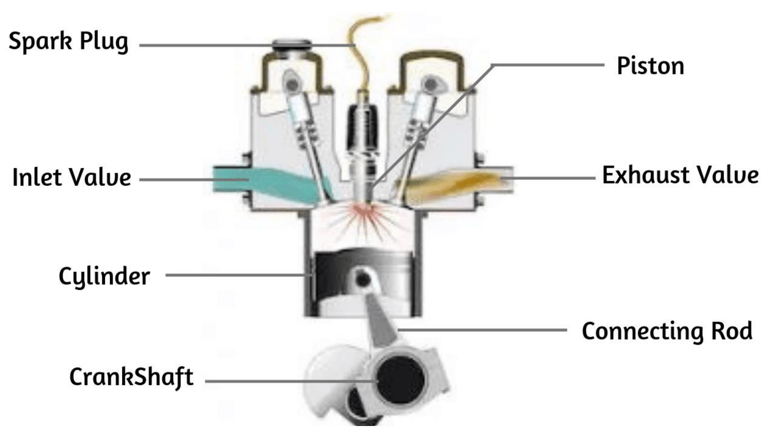


Figure 1.11: Spark Ignition Engine (http://www.mechanicaleducation.com/2019/03/Spark-ignition-engine-working.html)

2. **Combustion Ignition Engine**: The fuel is ignited with the help of heat of the compressed air. Common example are diesel powered engines.

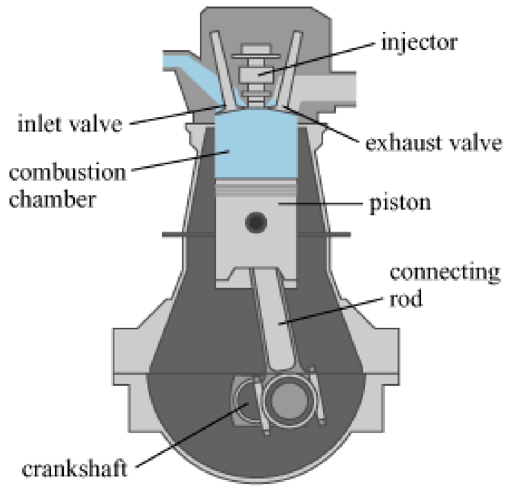


Figure 1.12: Compression Ignition Engine
(https://www.mechanicalbooster.com/2017/10/compression-ignition-engine.html)

1.1.2.6 With respect to number of cylinders

The type of engine with respect to number of cylinders used in engine are:

1. Single Cylinder Engine
2. Double Cylinder Engine
3. Multi Cylinder Engine

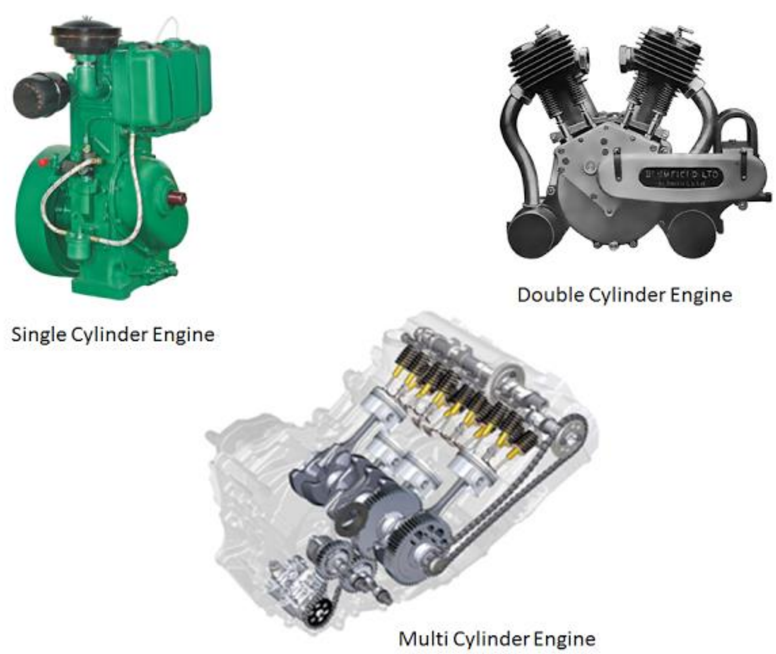


Figure 1.13: Engine type w.r.t number of cylinders
(https://www.mechanicalbooster.com/2016/08/different-types-of-engine.html)

1.1.2.7 With respect to arrangement of cylinders

The type of engine with respect to arrangement of cylinders used in engine are:

1. Vertical Engine: The type of engine in which the cylinders are arranged vertically.
2. Horizontal Engine: The type of engine in which the cylinders are arranged horizontally.
3. Radial Engine: The type of engine in which the cylinders are arranged like a wheel with crankcase at the middle.
4. V-Type Engine: The type of engine in which the cylinders are arranged like a V shape with cylinders placed at some angle with each other.
5. W-Type Engine: The type of engine in which the cylinder are arranged like a W shape in three rows. When the requirement for cylinders are 12 and 16, then this type of arrangement is used.
6. Opposed Cylinder engine: In this type of cylinder, the cylinders are placed opposite to each other.

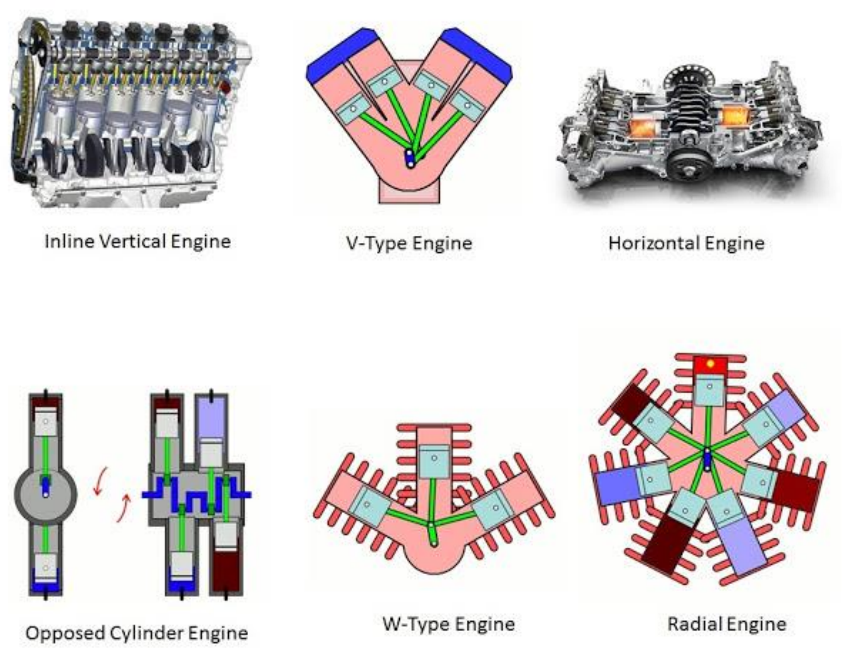


Figure 1.14: Engine type by cylinder arrangement
(https://www.mechanicalbooster.com/2016/08/different-types-of-engine.html)

1.1.2.8 With respect to cooling

The type of engine with respect to cooling system used in engine are:

1. **Air Cooled Engine**: In this type of engine, the engine is cooled with the help of air
2. **Water Cooled Engine**: In this type of engine, the engine is cooled with the help of water.

1.1.2.9 With respect to valve arrangement

The type of engine with respect to valve arrangement used in engine are:

1. L-Head Cylinder
2. I-Head Cylinder
3. F-Head Cylinder
4. T-Head Cylinder

1.1.3 Efficiency of Engines

In this modern era, it is highly demanding that the engines should be extremely efficient without compensating the power so that the vehicles should consume less fuel and give more power. The main reason for this thinking is because of the depleting resources and competitiveness. Also to reduce the exhaust gases which can damage the environment very bad. According to a research done by researchers, out of total 100% fuel energy only 21.5% energy is used by your car to move (Adaileh & Alahmer, 2015). These numbers are massive so it is important to reduce these losses incurred by the engine.

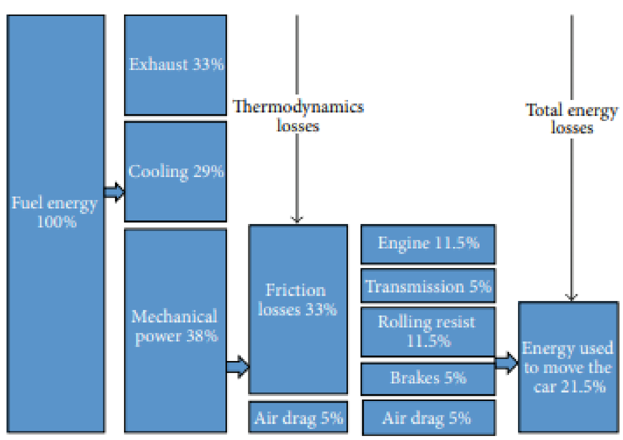


Figure 1.15: Losses of an Engine (Adaileh & Alahmer, 2015)

So it is very important to reduce these losses. But to make them efficient, the power obtained must not be compensated and engine should not be downsized. There are various methods used to reduce the losses. Boosting chargers are invented to make the cars efficient without compensating its power.

1.1.4 Boosting Chargers

Boosting chargers are used to make the automobile vehicles efficient and make them more powerful. These chargers used the exhaust gases released by the engine and some are directly connected with the crankshaft with the help of shaft. There are 33% exhaust gases released by the engine as shown in Fig 1.5, so by reusing these gases we can not only improve the efficiency but also make the environment cleaner. There are two types of chargers:

a. Turbocharger
b. Supercharger

1.1.4.1 Turbocharger

It is a type of boosting device which reuses the exhaust gases released by the engine and these exhaust gases runs the turbine, the turbine with the help of rotating assembly is connected to the compressor and both of them runs simultaneously when exhaust gases runs the turbine rotor. Fresh gases are intake by compressor inlet and compressor is used to compressor the fresh gases and then these gases are entered into the engine cylinder from compressor outlet. This whole process improves the combustion process hence improving the efficiency of the engine without increasing its size. This method not only improves the efficiency but also reduce pollution in the surrounding environment. Components of a turbocharger are:

a. Compressor rotor
b. Turbine rotor
c. Wastegate
d. Rotating Assembly
e. Water Injection
f. Turbo Housing

g. Oil feed/drain lines

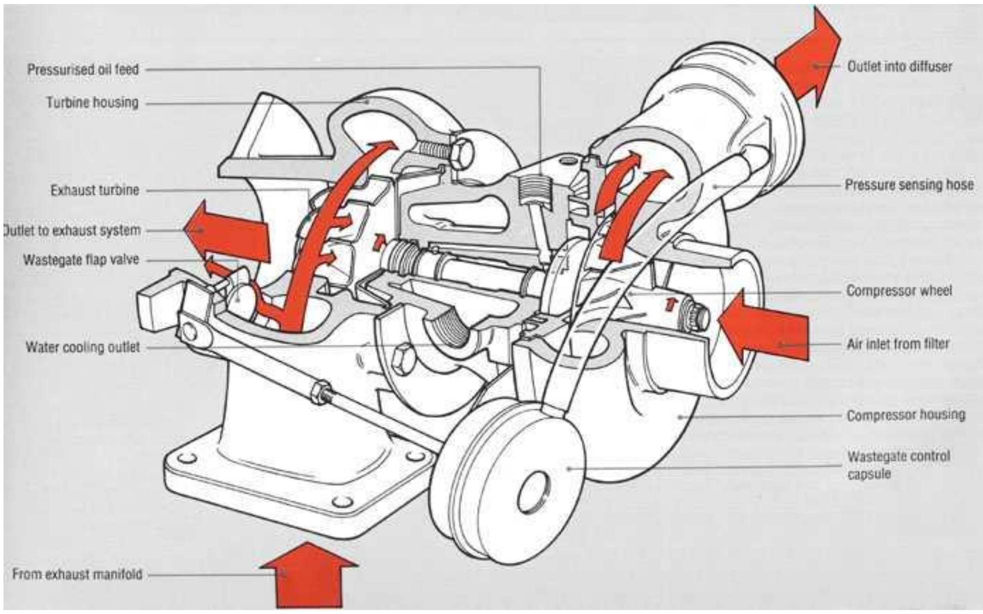


Figure 1.16: Turbocharger (https://www.brighthubengineering.com/marine-engines-machinery/41368-components-of-a-turbocharger/)

1.1.4.2 Supercharger

It is a type of boosting device which increase the air pressure that is supplied to an engine. Supercharger uses the crankshaft for producing the power for an engine. It is connected to the engine by the help of belt or gear to crankshaft. When crankshaft of engine moves, which is connected to compressor of supercharger and drives the compressor also. So as long as the engine is working supercharger also works. But it reduces efficiency of engine as it helps to drive the compressor of supercharger which is directly connected to it. Components of supercharger are:

a. Compressor
b. Impeller
c. Housing
d. Pulley
e. Oil Pump
f. Bearing

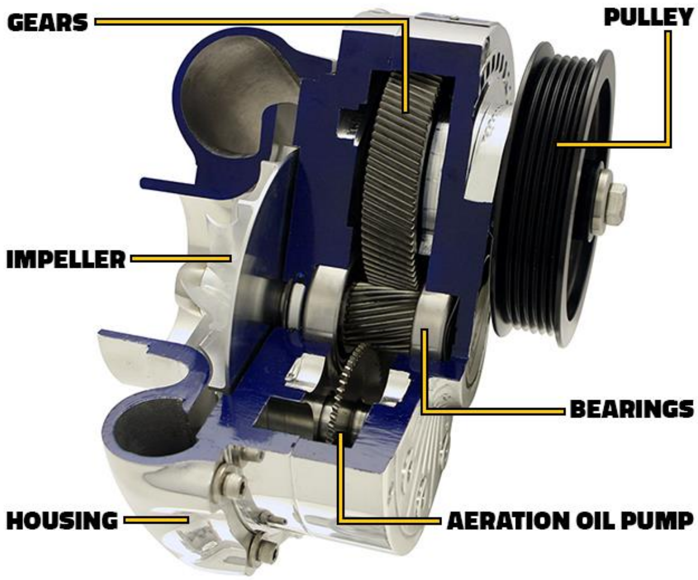


Figure 1.17: Supercharger (https://www.procharger.com/centrifugal-supercharger)

1.1.4.3 Difference between Turbo and Supercharger

Table 1.2: Turbocharger and Supercharger

Feature	Turbocharger	Supercharger
Response Time	More	Less
Efficient	More	Less
Driven by	Self	Engine
Lag	More	Less

1.1.4.4 Types of Turbocharger

Following are the types of turbocharger:

a. Single Turbine
b. Twin Turbine
c. Variable Geometry Turbo
d. Fixed Geometry Turbo
e. Electric Turbochargers.

Fixed Geometry Turbocharger (FGT), is a type of turbocharger in which the gas flow passage's width is changed by repositioning the stator guide blades keeping the angle of inlet nozzle constant (Serrano, Arnau, Dolz, Tiseira, & Cervelló, 2008).

As the name suggests, variable Turbocharger is a type of turbocharger in which geometry of the turbocharger can be changed. The angle of the inlet nozzles of the turbine can be changed and by changing it, the air flow angle on blades of turbines is also changed with will change the effective area of the turbine. By doing so, the energy transferred can be changed, so it affects the speed of turbocharger and boost pressure. The main advantage of VGT is that, it is very flexible, having capability of proving various pressure ratios. The response of VGT is also better than Fixed Geometry Turbo (Hawley, Wallace, Cox, Horrocks, & Bird, 1999).

An electric turbocharger is a one in which motor is used along with the Turbo. In Electric Turbocharger, the motor is connected with the compressor hence improving the response time. The boost pressure of the compressor is controlled by motor instead of exhaust turbine. Its advantages are lowering the Fuel consumption of vehicle, the reduction of NOx emissions along with downsizing the engine. Electric turbocharger is further classified into two types which are hybrid turbocharger in which the orthodox turbocharger is used with the motor and the other type in which the turbo doesn’t use the exhaust gas (Yamashita et al., 2010).

CHAPTER 2: LITERATURE REVIEW

(Benajes, Luján, Bermúdez, & Serrano, 2002) discussed the causes of the turbo-lag problem. According to him, he classified the causes in three groups: 1) mechanical- it includes the inertia and friction incurred by the turbocharger and all the moving parts of the engine, 2) thermal and 3) fluid dynamic phenomena- these causes includes the energy transfer and mass transfer from exhaust manifold to the turbo turbine and then from compressor to the intake manifold. (IBARAKI, 2006) used the hybrid turbocharger with motor connected with the compressor so that it can move the compressor even in cold start when there are negligible amount of exhaust gases to run compressor so that Turbo Lag is reduced and the transient response of turbocharger is improved. By using it, the transient response of Turbocharger was improved but the problem with this kind of turbocharger is that external energy is required to run the motor. He also compared the results with variable geometry turbocharger and found that hybrid turbocharger has 33% better response than Variable Geometry Turbocharger. (Tetsui, 2002) improved the transient response by decreasing the moment of inertia of rotating parts i-e turbine. He used the alloys to make turbine rotor that are very light and are made of Ni-based Alloys. By using the light material, the response of the turbochargers was increased but the main problem of this type of light material is that the maximum temperature these types of material can bear is less than the temperature of exhaust gases so these type of materials cannot be exposed for long time. (Terdich, Ricardo, Howey, D. Copeland, & Costall, 2011) provided the solution for the turbo-lag by the addition of electric assist motor/generator which will act as a motor in the start when there are insufficient gases and will act as a generator when the engine is on surge and the gases will be used to generate energy instead of going out through wastegate. The rpm of the motor should be high so that it can move with the turbocharger without any problem. By using this type of turbocharger he improved the efficiency of the engine along with the better transient response. The turbochargers improve the efficiency of the engine and boosts the power output of the time but the Turbo-lag is the biggest problem which effects the drivability of the vehicle. (Lee & Choi, 2002) provided the solution to tackle this problem and increasing the transient response of the turbocharger by injecting air at the compressor exit to intake manifold. The transient response is improved by increasing the pressure of injecting air. (Filipi, Wang, & Assanis, 2001) also introduced the VGT model to improve the transient response of a diesel powered engine. (Zsiga, Voser, Onder, & Guzzella, 2013) also discussed the problem of turbo-lag incurred in turbocharged engine. He used a boost valve on to the intake manifold of the engine and injected air directly to the intake manifold and see the results. By using this technology he also avoided the surge without using the wastegate. From the results he concluded that boosting the intake manifold with air can improve the transient response. (Zhongchang Liu, 2018) used different strategies to tackle the problem of turbo-lag. He used full stage loading (FSL-the loading will be constant for the whole transient time) and sectional stage loading (SSL-wait for some time at certain load) and he observed that in SSL the transient rate was improved and the soot emissions were also reduced. (Oliver S. Gilkes, Mishra, Rao, & D. Fieldhouse, 2007) presented the work for the improvement in transient response of the engine. This problem is one of the biggest obstacle to use turbocharger at wide scale so to tackle it is very important. They introduced the two way injecting system. In this system air is injected into the intake manifold of the engine or to the compressor of the turbocharger or both. From the results they concluded that the transient response is significantly improved by using this method and two way injection system improves the efficiency more than single way injection. (O. S. Gilkes, Mishra, Fieldhouse, & Rao, 2008) also used the two way injection method to improve transient response and decrease the emissions. They also compared the air injection of compressor with intake manifold air injection and from the results they concluded that the air injection from turbocharger compressor gives more positive results than air injection from intake manifold. (Galindo, Luján, Serrano, Dolz, & Guilain, 2006) developed a model to predict the transient response of High speed direct Injection (HSDI) Turbo Engines to be implemented in a 1-D Dynamic model by varying the thermal inertia of the system. The model was verified with the help of various tests. The thickness of piston wall was also varied to see the performance of engine against the changed values. With the help of experiments it was seen that with the higher thermal inertia, the response time was increased to 1.7%. To improve the transient response of the engine, the only way was to lower thermal inertia or we had to maximize the injected fuel rate in the first stage to improve the transient response which will not be economical.

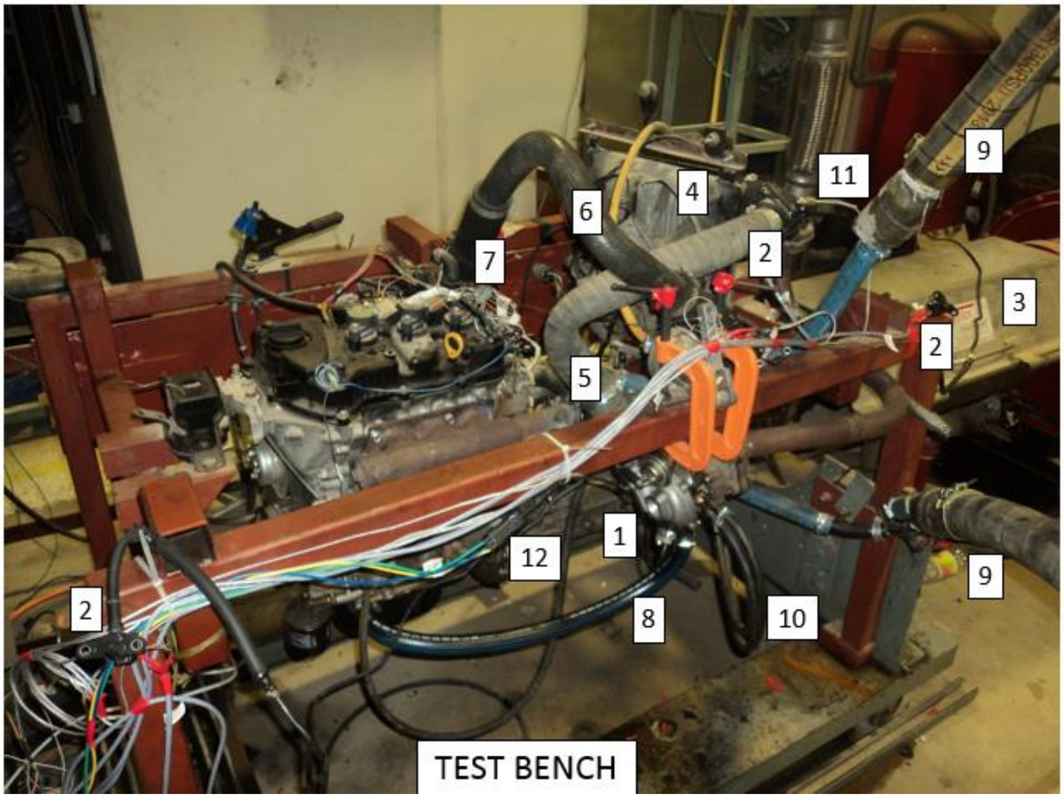
CHAPTER 3: EXPERIMENTAL SETUP

3.1 TEST BENCH

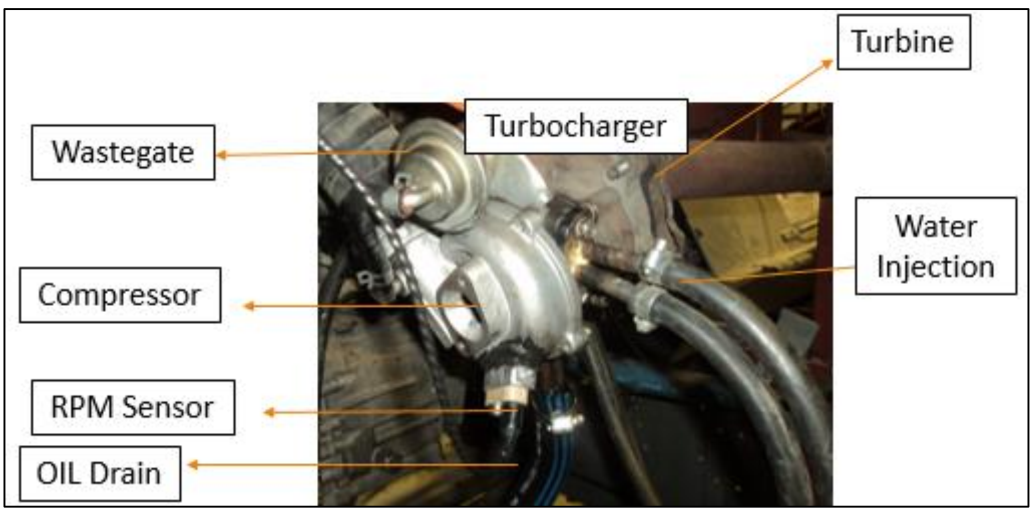
The experimentation was done on a MIRA 660 cc engine. The specifications of the engine is given in the table below.

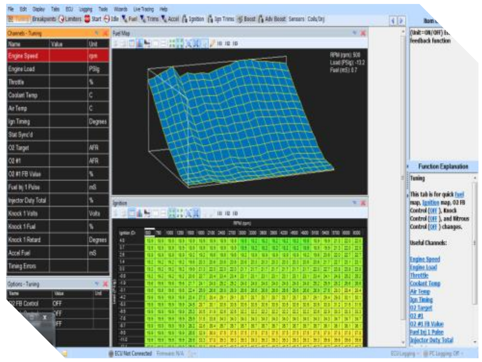
Table 1.3: Engine Specifications

Vehicle	Daihatsu Mira
Engine type	EFI (Gasoline)
Displacement	660 cc
Bore (Diameter of Cylinder)	63 mm
Stroke	70.4 mm
No of cylinders	3 (Inline)
Cycles	4
Minimum-Maximum RPM	
Rated power	58 HP @ 7600 RPM
Rated torque	60 Nm/5200 rpm
Turbocharger	IHI Rhb31
Idle speed	
Compression ratio	11.3:1
Connecting rod length	
Combustion system	
Dynamometer	
Length	3395 mm
Height	1500 mm
Width	1475 mm



1- Turbocharger
2- Map Sensors
3- Dynamometer
4- ChargeCooler
5- Turbo Compressor Outlet
6- ChargeCooler Outlet
7- Intake Manifold
8- Turbo oil drain
9- Engine Cooling system pipes
10- Turbo water injection
11- Thermocouple
12- Turbo oil supply




3.2 Instrumentation

Table 1.4: Sensors Used

Sensor Type	Sensor Description	DAQ Card Used
Turbo Speed	BorgWarner Turbospeed Sensor	NI 9401
Pressure	Toyota Vigo Map Sensor	NI 9214
Temperature	EGT K-Type Thermocouple	NI 9219

3.2.1 Map Sensor:

MAP stands for Manifold absolute pressure. It is a sensor that is used for measuring the manifold pressure of gases. It can be used on compressor or turbine. This sensor is very important because it sends signal to the engine which then control the injection timing and AFR according to the signal received. It has a flexible diaphragm. When the pressure of the air changes, the diaphragm also moves and is proportional to the pressure. It is connected with the electronic signal which generates voltage signal ranges from input voltage 5V or 12V. At highest temperature the voltage will be approx. 5V and at minimum temperature the voltage will be 0.2V. At atmospheric pressure the voltage will range from 1-2V. We are using four Toyota VIGO Map Sensor. One map sensor is connected at the compressor outlet, one after chargecooler outlet, one at turbine inlet and the last one at turbine outlet.

Following are the steps to connect MAP Sensor to NI 9214:

- Check for the terminals of the MAP sensor i-e signal, ground and 5V supply.

- Identify the channel to which sensor is attached and from the DAQ Software (Labview) select the channel to which the sensor is connected.
- Make front and block diagram
- Click acquire signal, Analog input and then voltage.
- Calibrate the pressure values from 0-5V to 0-85 PSI. Because 0V is at 0 PSI and 5V is at 85 PSI. This is done with the help of interpolation.
- Write the values to save the data.
- Click run to take reading.

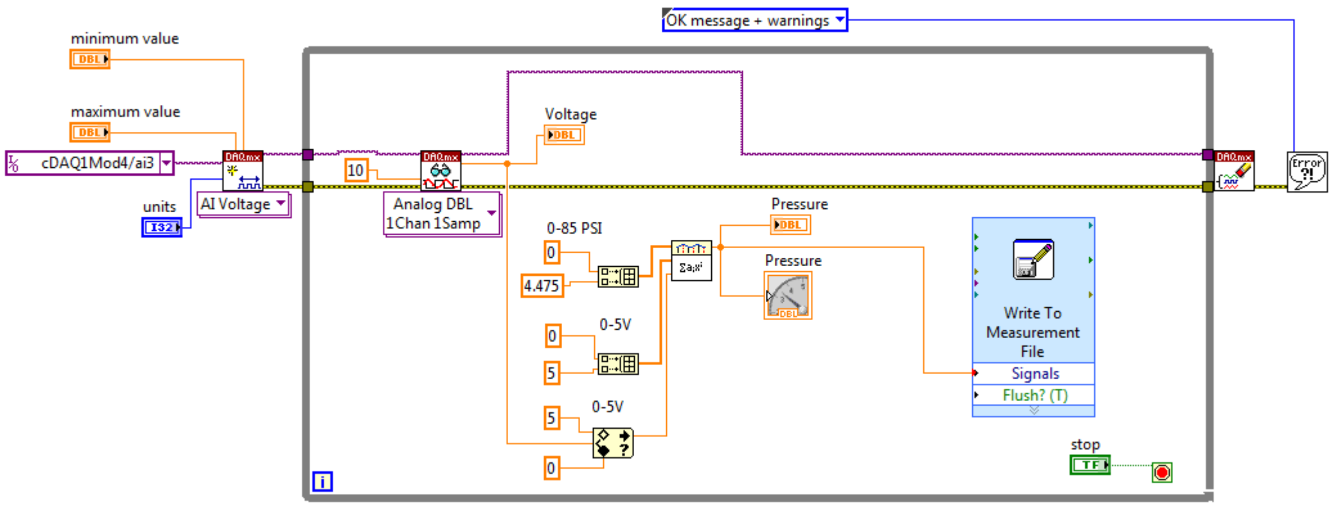


Figure 1.18: Block Panel of MAP Sensor

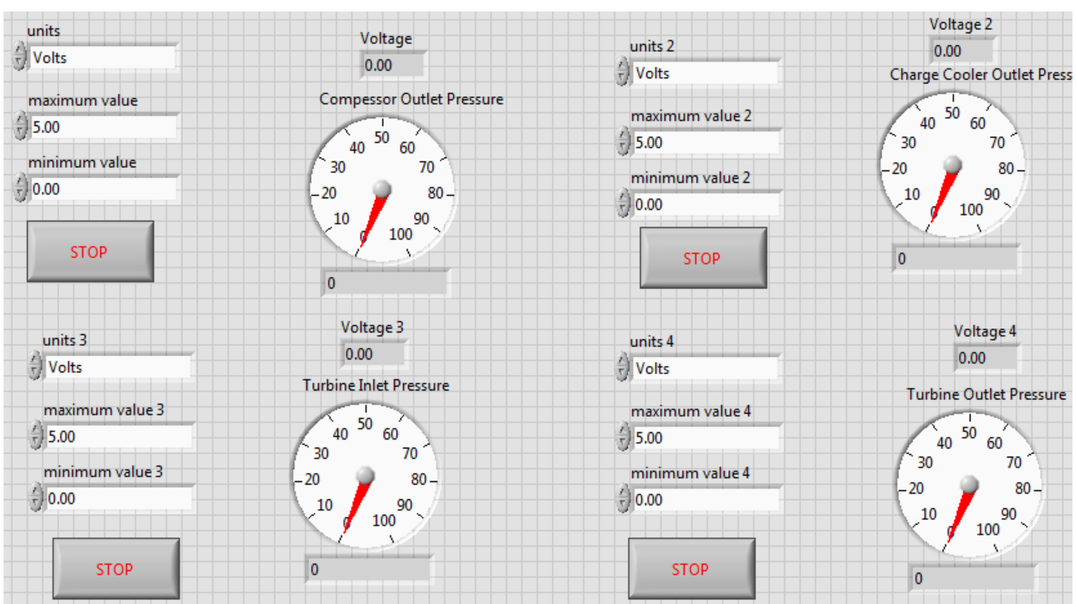


Figure 1.19: Front Panel of Map Sensor

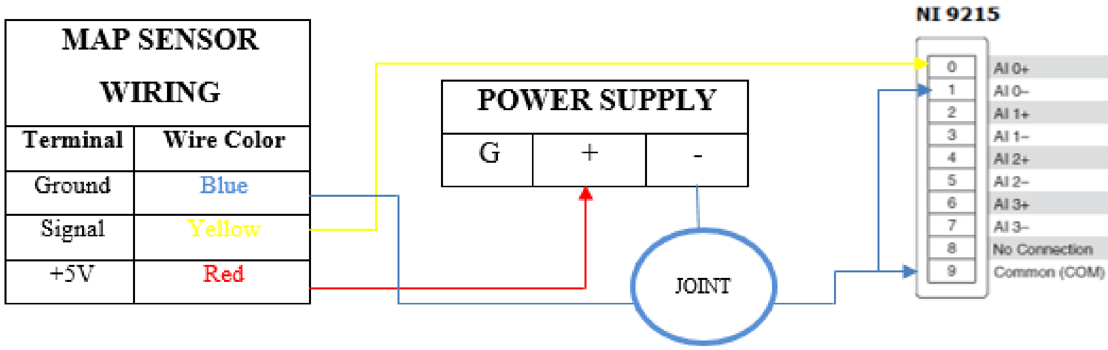
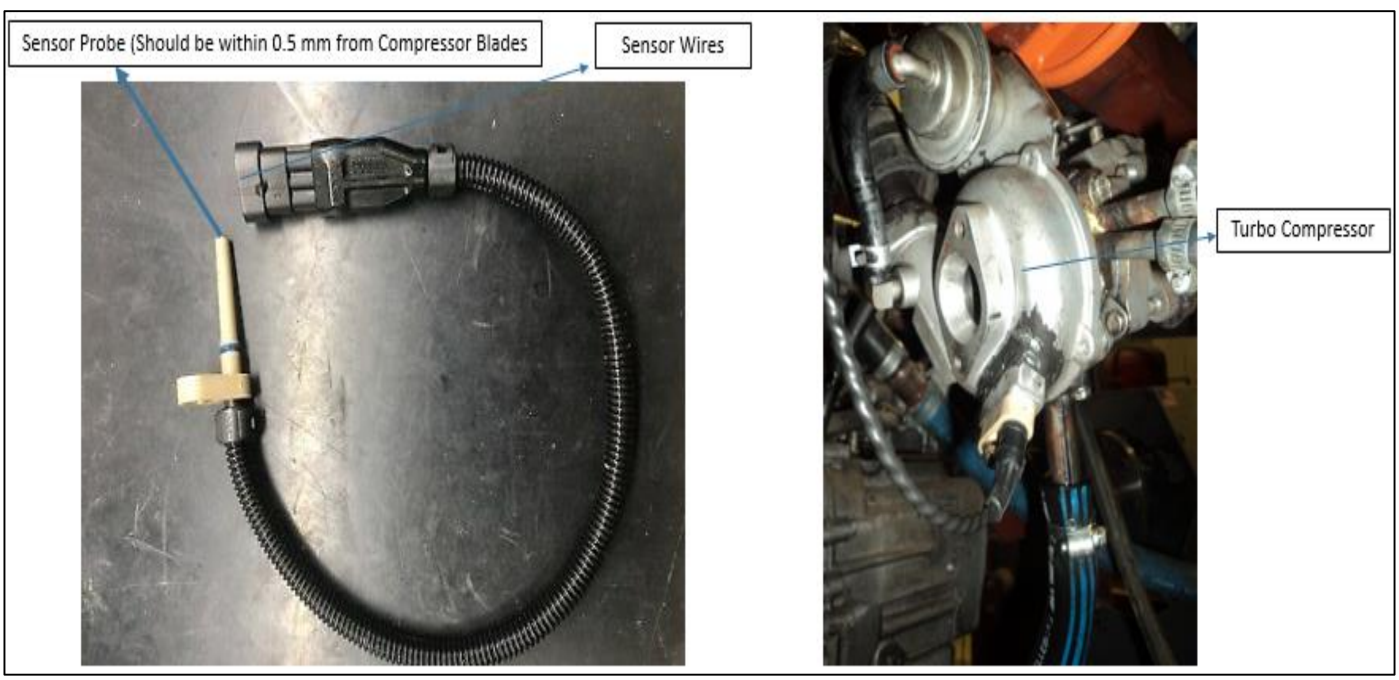


Figure 1.20: Wiring of MAP Sensor

3.2.2 Turbo Speed Sensor:

It is used for measuring the speed of compressor blades of turbocharger. This sensor works on the principle of EDDY Current. The sensor is powered by a 5V power supply which sends the data and receives it back. It has an electronic system which converts the voltage to frequency which is then converted into RPM by multiplying it with 60.It is mounted on compressor housing at an angle of 45 degrees and just 0.5mm away from compressor blades to measure accurate values. The speed sensor which we are using is BorgWarner Turbospeed sensor.



Following are the steps to connect Turbo speed sensor to NI 9401:

- Check the terminals of Turbospeed sensor i-e signal, ground and 5V supply.
- Identify the channel to which sensor is attached and from the DAQ Software (Labview) select the channel to which the sensor is connected.
- Make front and block diagram
- Click acquire signal, counter input and then frequency.
- Multiply that frequency value with 60 to convert it into RPM.
- The yellow wire is taken as signal which is connected to PFI0, blue as common and green as 5V.
- Write the values to save the data.
- Click run to take reading.

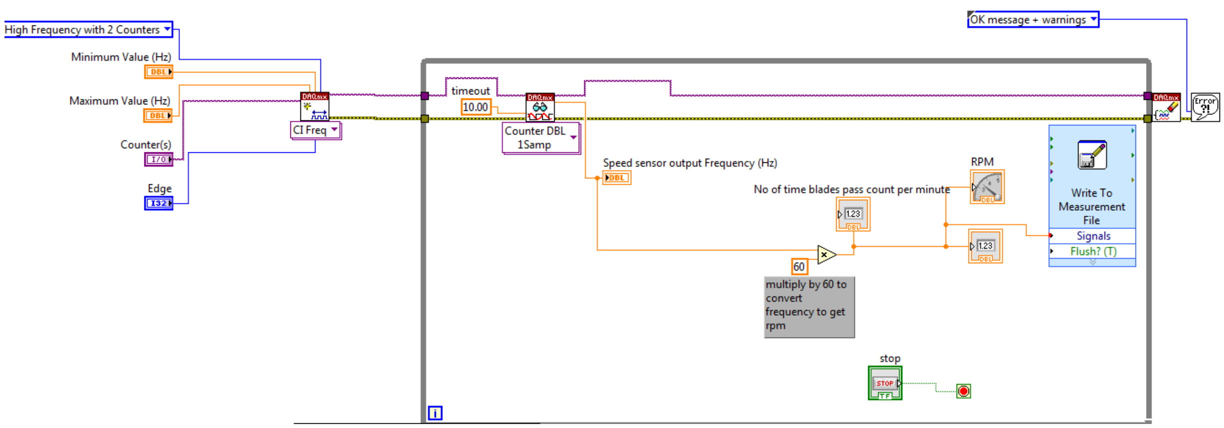


Figure 1.21: Block Panel of RPM Sensor

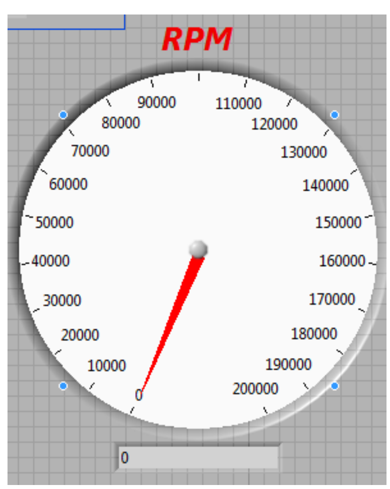


Figure 1.22: Front Panel of RPM Sensor

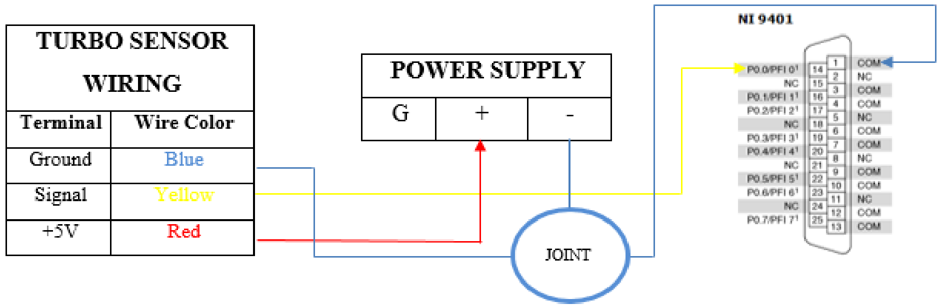
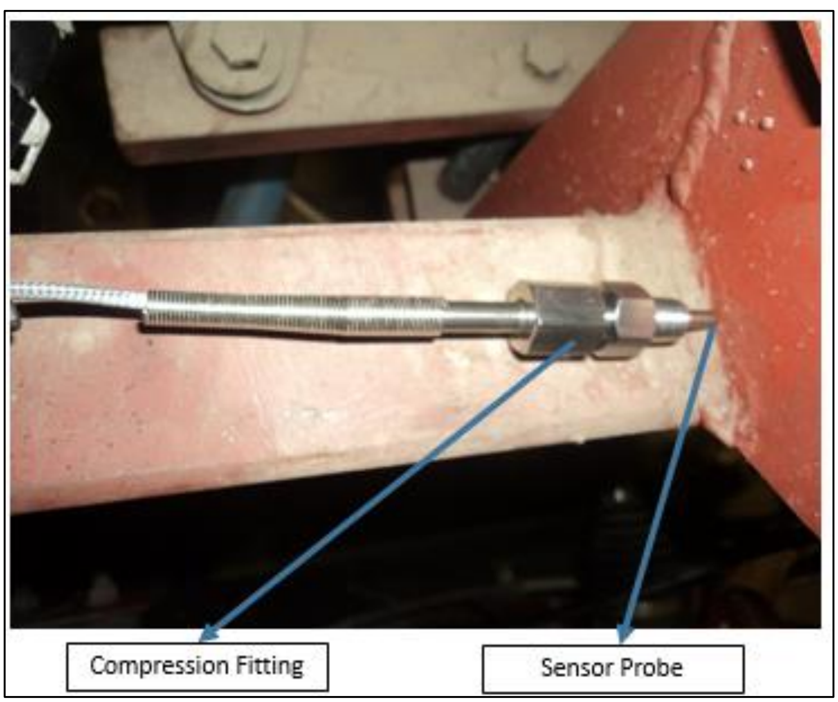
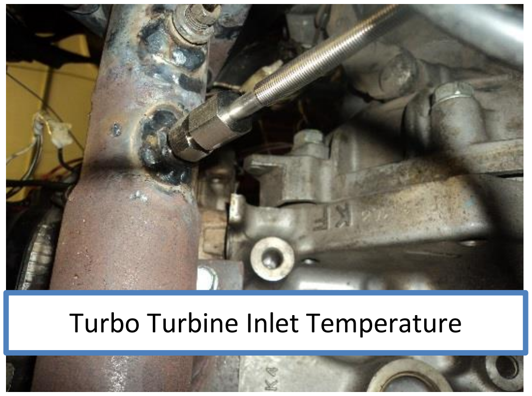


Figure 1.23: Wiring of Turbo Speed Sensor

3.2.3 Temperature Sensor:

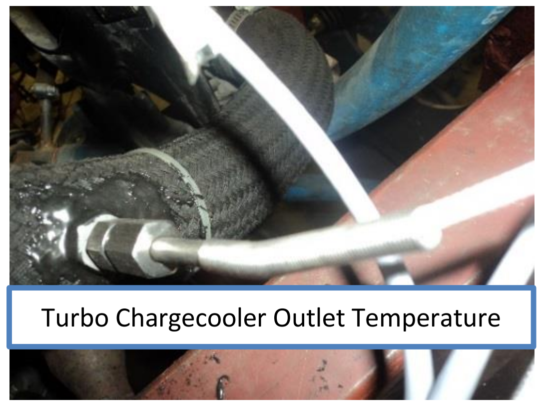
It is a sensor which is used to measure the temperature of exhaust gases. Thermocouple has two wires made from different metals which are joined at one end. This junction is engaged to the surface to be measured. After the engagement the metals starts to deform and the resistance changes. When the resistance of the metals changes, the changes in voltage is measured. Generally, the thermocouple gives output signal in millivolts. They are preferred because of low cost easy compatibility and good range. We are using K-Type thermocouple with compression fitting. It is also called exhaust gas thermocouple. As compression fitting has an olive ring and because of it the exhaust gases leakages can be avoided.




Turbo Turbine Inlet Temperature


Turbo Turbine Outlet Temperature


Turbo Compressor Outlet Temperature


Turbo Chargecooler Outlet Temperature

Following are the steps to connect Thermocouple to NI 9219:

- Check the terminals of Turbospeed sensor i-e positive and negative.
- Identify the channel to which sensor is attached and from the DAQ Software (Labview) select the channel to which the sensor is connected.
- Make front and block diagram
- Click acquire signal, analog input, temperature and then thermocouple.
- The DAQ Card we are using has built-in amplification and cold Junction compensation (CJC), so cjc source will be built-in, the temperature range will be 0-1200 C and thermocouple type is K.
- The green wire is taken as positive and the yellow wire as negative.
- Write the values to save the data.
- Click run to take reading.

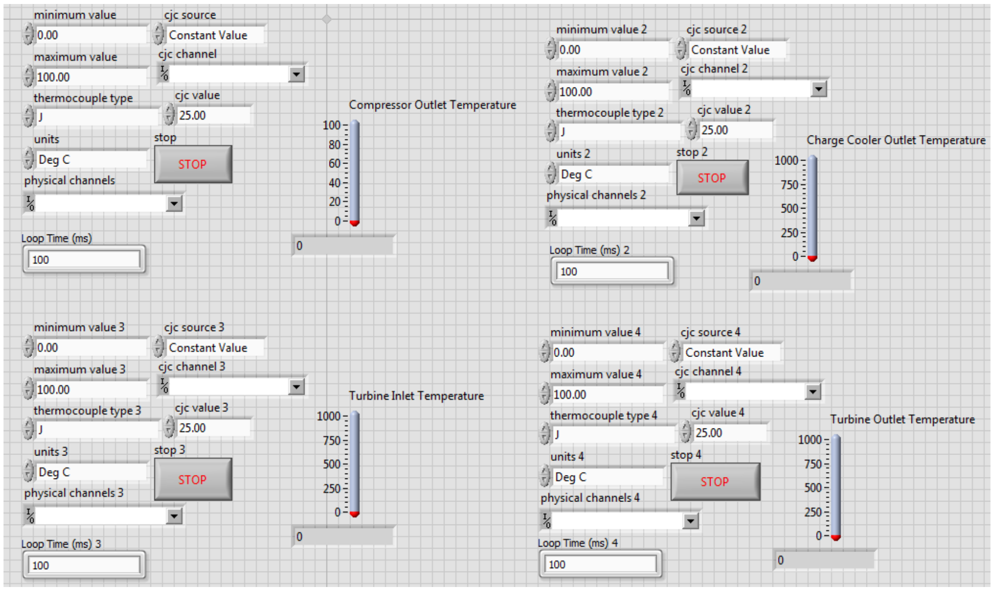


Figure 1.24: Front Panel of Thermocouple

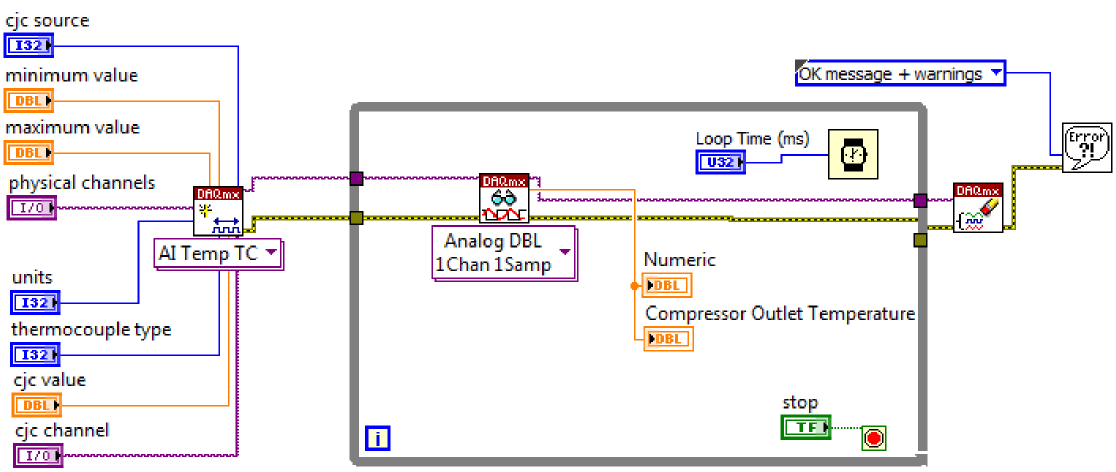


Figure 1.25: Block Panel of Thermocouple

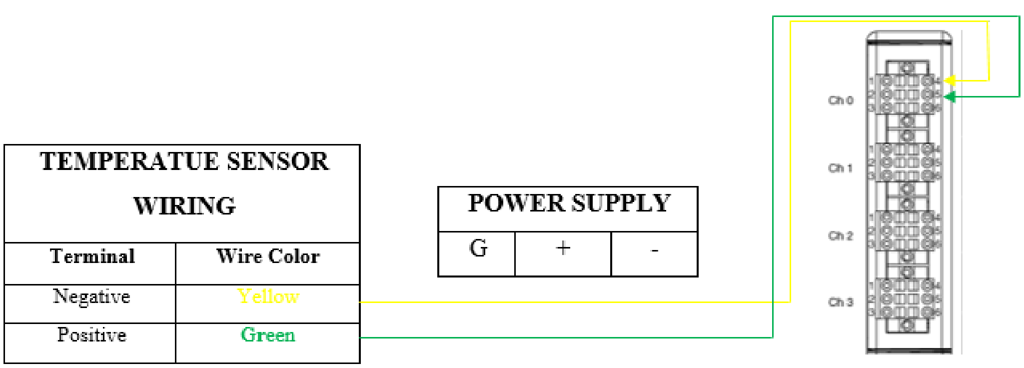


Figure 1.26: Wiring of Thermocouple

3.3 Moment of Inertia

For finding the moment of Inertia, we used the falling mass method. We constructed the instrument having one side on the general bearing and the other side with a nut opener. First we attached different masses on the shaft and drop it from top and noted the time of fall and by using formulas we found the moment of inertia. Then we connected one side of the instrument to the nut of the turbocharger's turbine blade and then we release the weight so that it can fall. We noted the time and find the moment of inertia by using the formula. This moment of inertia was the combine inertia of Turbo and flywheel.

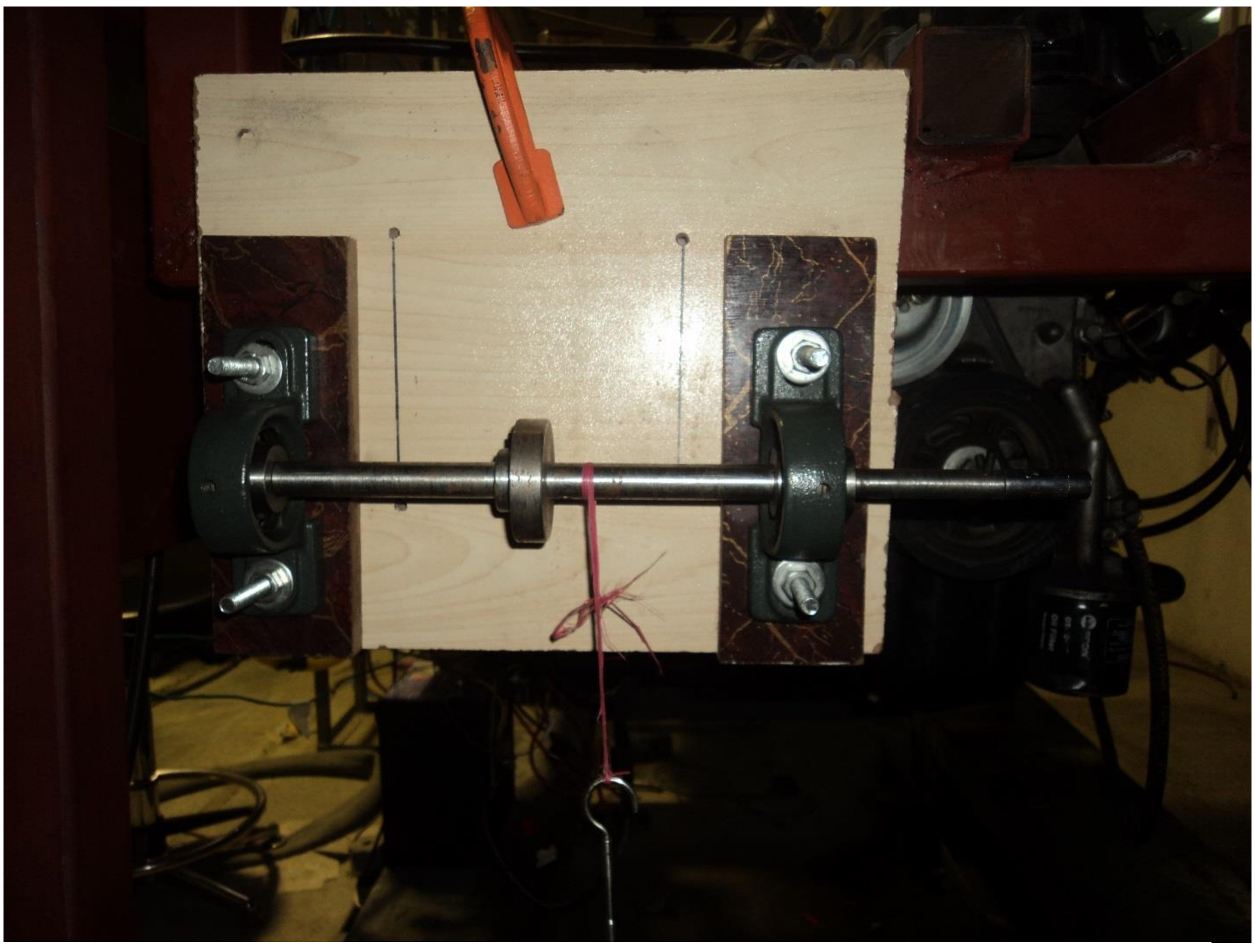


Figure 1.27 : Instrument for measuring moment of inertia

Following are the calculations done to find moment of inertia:

Diameter of axle (D): 1.5cm
Mass of Flywheel (M):
Radius of Flywheel (r): 2.5cm

I = Moment of Inertia ($g*cm^{-2}$)
t_{avg} = Average time of fall (sec)
T = Tension in the string (N)
A = Acceleration ($cm*s^{-2}$)
ą = Angular Acceleration ($rad*s^{-2}$)
g = acceleration due to gravity ($cm*s^{-2}$)
Ʈ = Torque (N*cm)
d = distance of fall (cm)
m = Hanging mass (g)

Table 1.5: Moment of Inertia Values of Flywheel

Sr. No	d	r	m	g	t	A	ą	T	Ţ	MOI	% Error
1	64.5	0.8	700	980	0.7	287.4	383.2	484841.6	363631.2	949.0	1.4
2	64.5	0.8	1200	980	0.6	404.1	538.8	691075.6	518306.7	962.0	2.7
3	64.5	0.8	1700	980	0.5	496.0	661.3	822862.7	617147.1	933.3	-0.2
4	64.5	0.8	2200	980	0.5	559.9	746.5	924229.2	693171.9	928.5	-0.8
5	30.4	0.8	700	980	0.5	295.3	393.7	479310.6	359482.9	913.1	-2.5
6	30.4	0.8	1200	980	0.4	410.6	547.5	683289.6	512467.2	936.1	0.1
7	30.4	0.8	1700	980	0.4	496.8	662.4	821412.2	616059.2	930.0	-0.6
8	30.4	0.8	2200	980	0.3	558.9	745.1	926505.1	694878.8	932.5	-0.3
									Average	**935.6**	

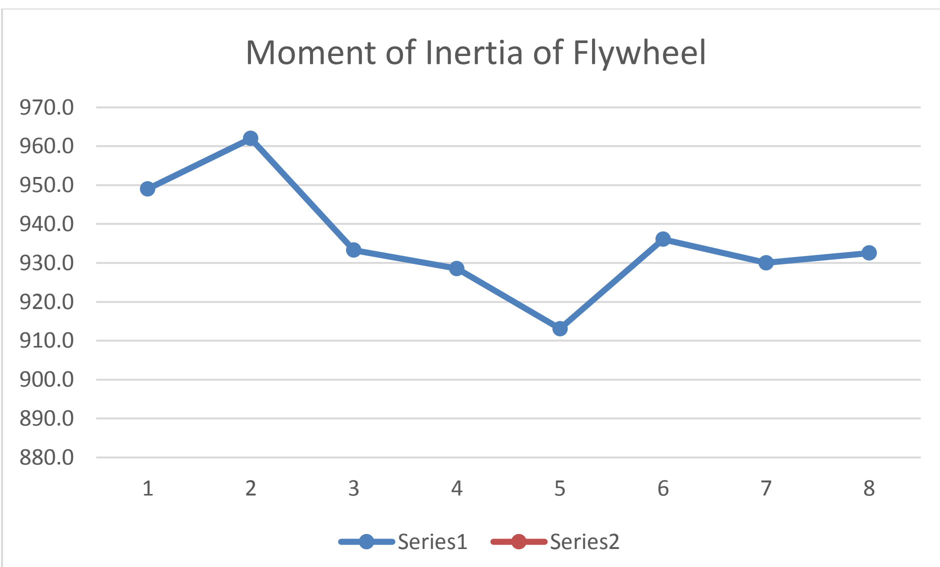
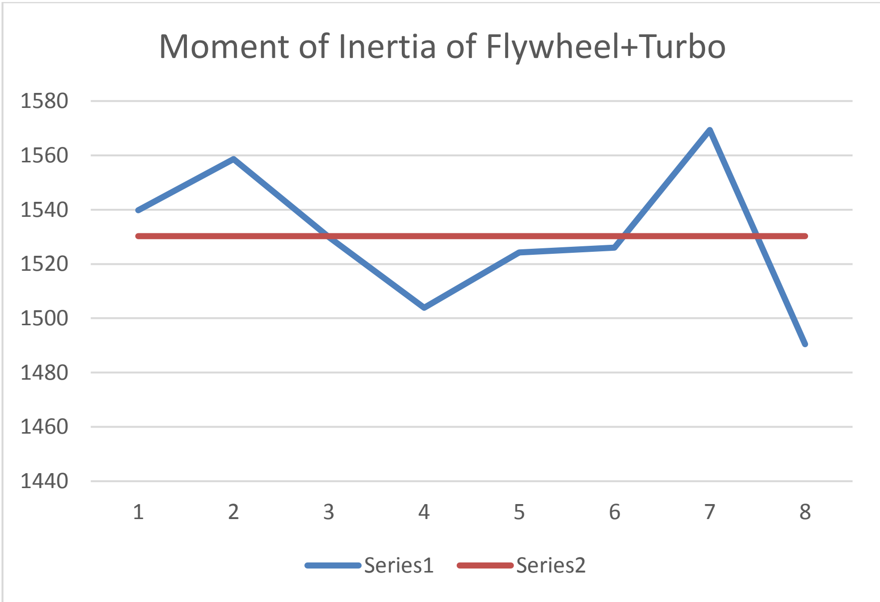


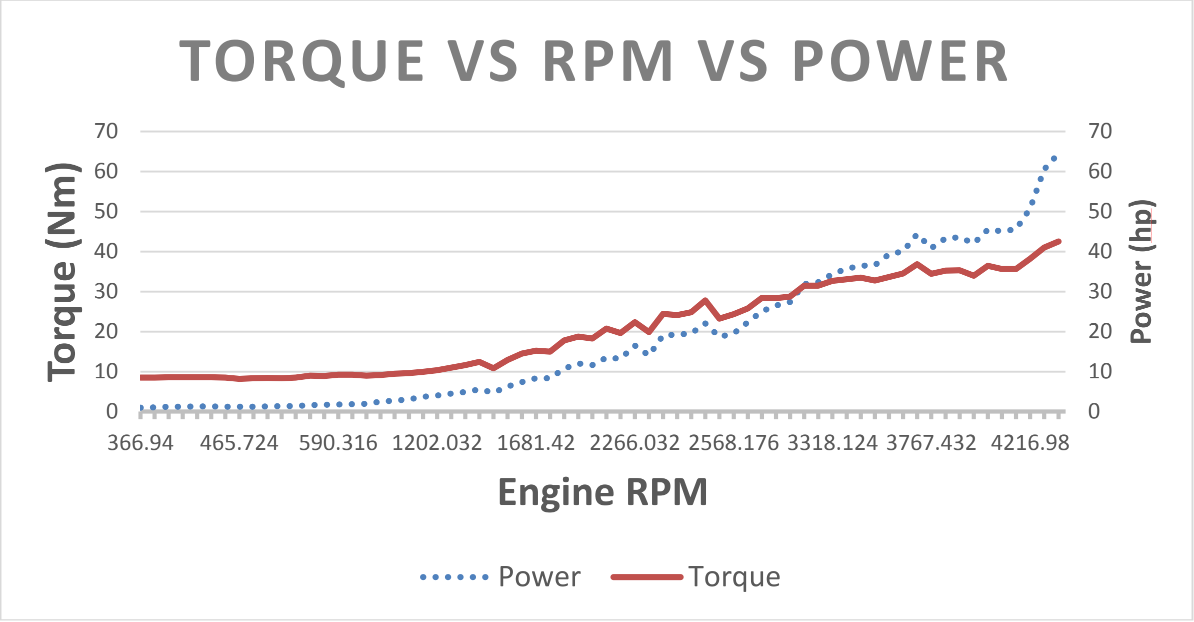
Table 1.6: Moment of Inertia Values of Flywheel and Turbocharger

Sr. No	d	r	m	g	t	A	ą	T	Ţ	MOI	% Error
1	64.5	0.8	700	980	0.8	199.6	266.1	546306.7	409730.0	1539.9	0.6
2	64.5	0.8	1200	980	0.7	296.1	394.9	820628.1	615471.1	1558.7	1.8
3	64.5	0.8	1700	980	0.6	376.9	502.6	1025193.5	768895.1	1529.9	0.0
4	64.5	0.8	2200	980	0.5	442.4	589.8	1182749.0	887061.7	1503.9	-1.8
5	30.4	0.8	700	980	0.6	201.2	268.3	545166.9	408875.2	1524.2	-0.4
6	30.4	0.8	1200	980	0.5	300.5	400.7	815348.1	611511.1	1526.0	-0.3
7	30.4	0.8	1700	980	0.4	371.0	494.7	1035230.3	776422.7	1569.4	2.5
8	30.4	0.8	2200	980	0.4	444.6	592.7	1177972.2	883479.2	1490.5	-2.7
									Average	**1530.3**	

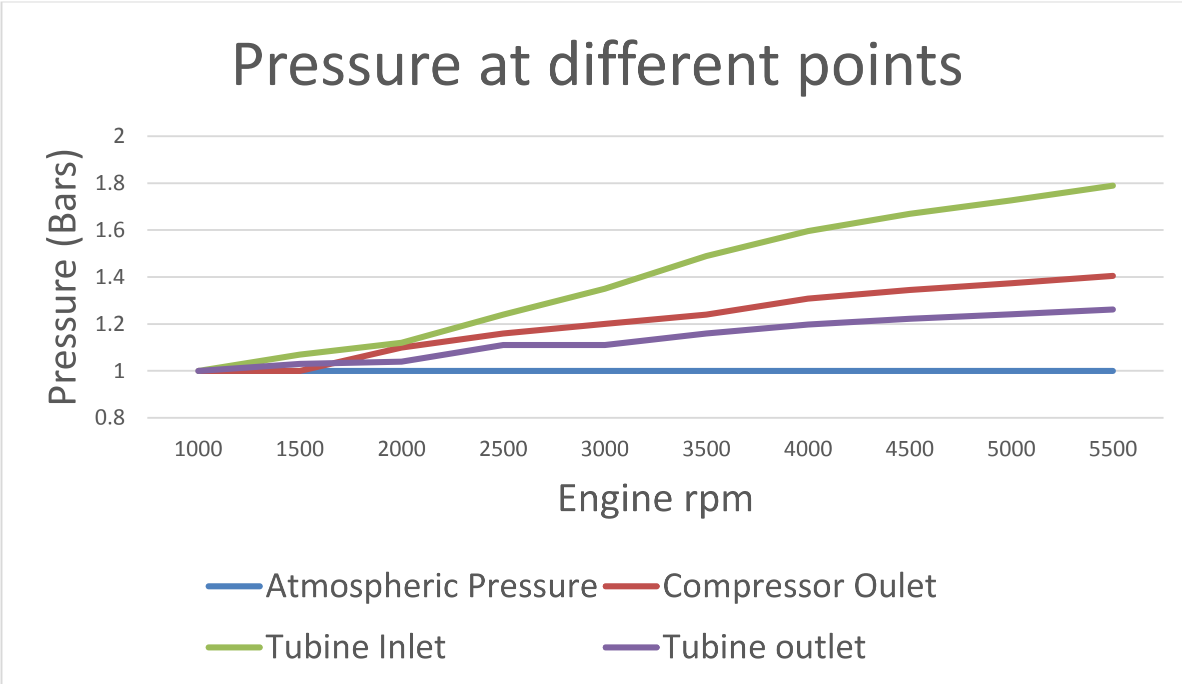


CHAPTER 4: RESULTS

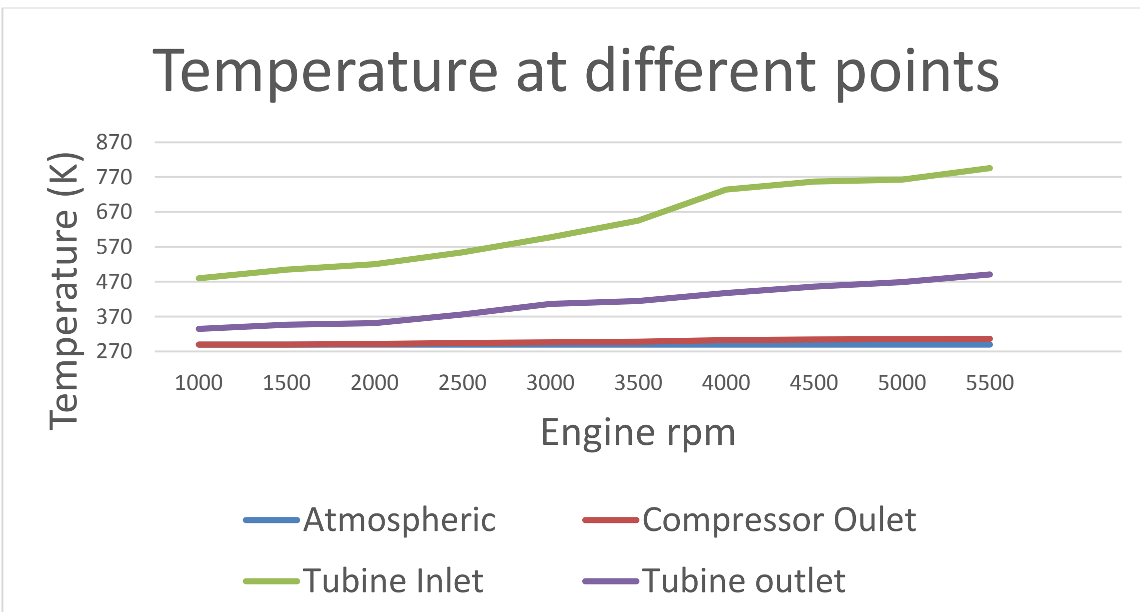
We operated the engine at different RPM and hold it for some time to check the behavior of the engine. As we can see in the graph that as we start increasing the engine RPM, the power and torque of the system also increasing till the certain and after 4500 RPM the power of the system is increasing but the toque stat to decease after this point. This is shown in the following graph.



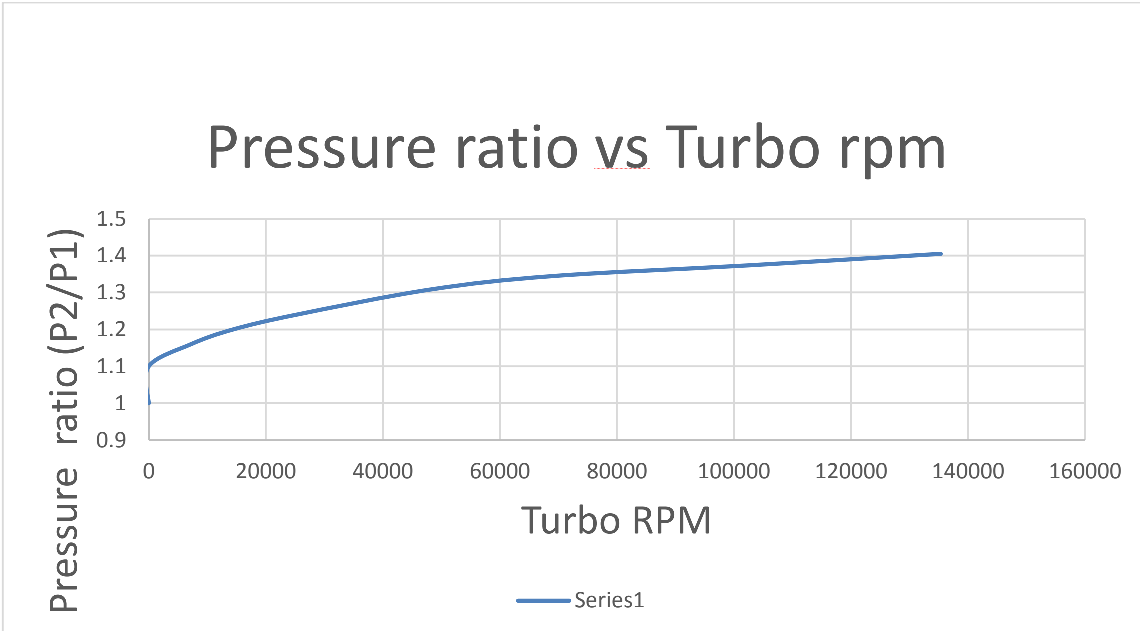
At the start the pressure of all the points is same but as we start pressing the throttle, the turbine inlet pressure shoots and is at 1.8 bas at 5500 RPM but the pressure ratio of compressor and turbine remains equal.



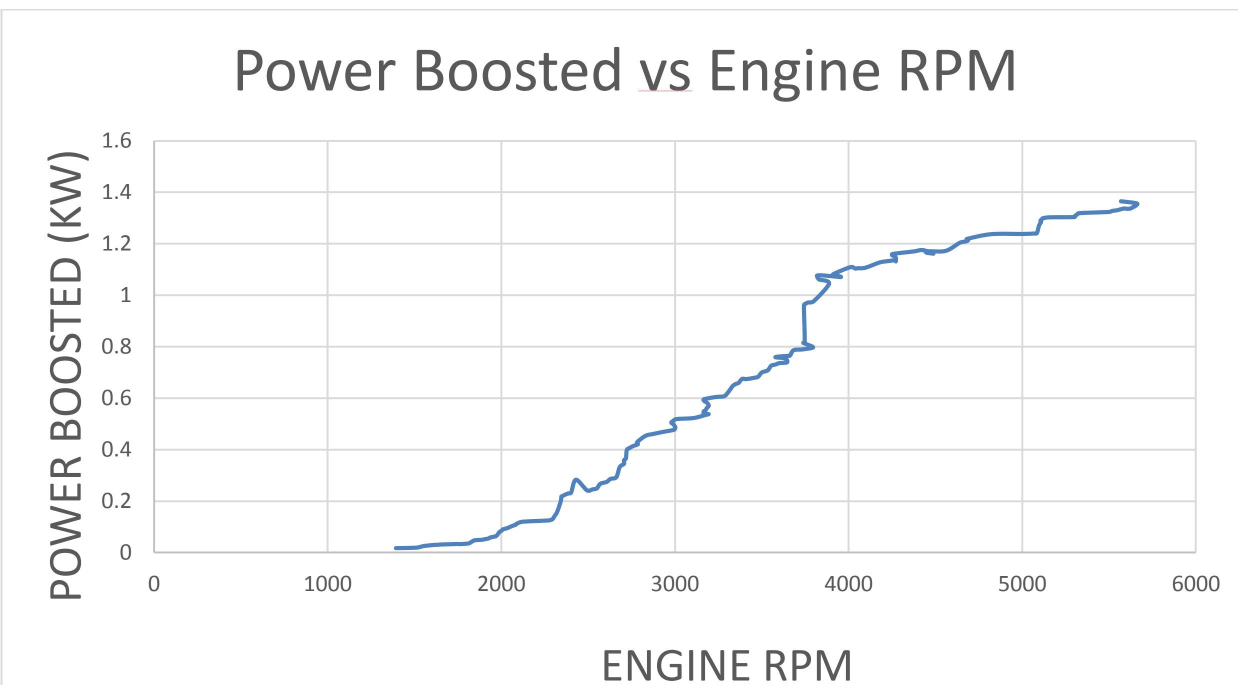
The temperature of the turbine inlet is maximum which is at 800K at 5500 RPM but the compressor outlet temperature is nearly same as the atmospheric pressure.



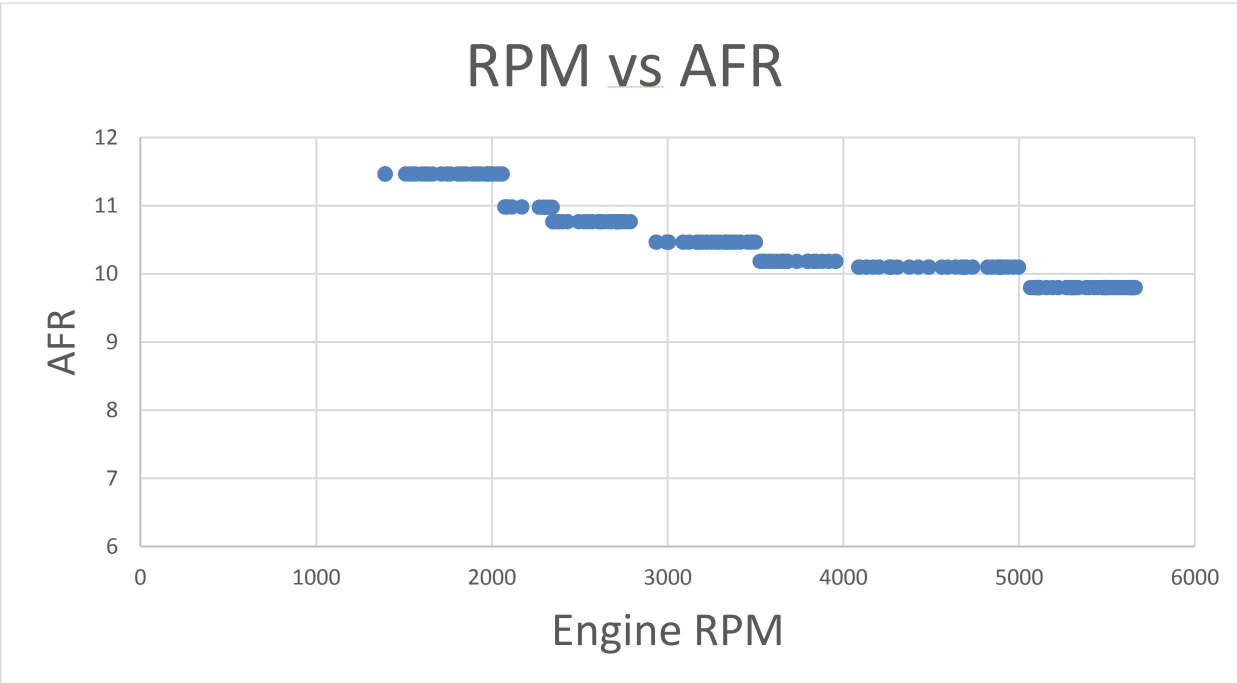
As we press the throttle, the concentration of exhaust gases increases, which will help moving the compressor blades more faster and when the RPM of compressor blades increases, it will compressor more air and as a result pressure ratio of the compressor will increase as we can see in the following figure.



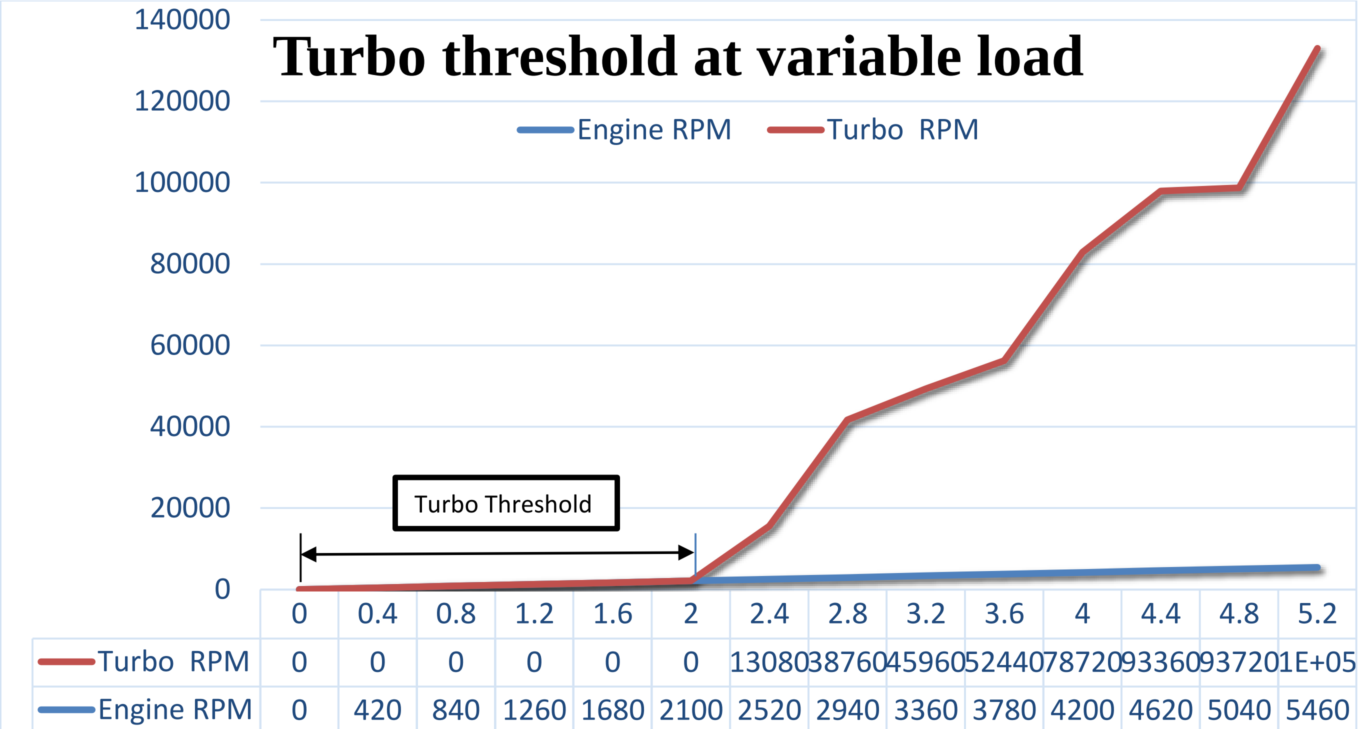
As we press the throttle, the concentration of exhaust gases increases, as a result more air is boosted into the intake manifold of the engine and the power boosted by the engine will increase as we can see in the figure below.



By increasing the RPM of the engine, turbo RPM will also increase, which will result in more compressed air into the intake manifold. So, more compressed air means we need more fuel to bun the air, that's why when RPM increases, we need to decease the AFR.

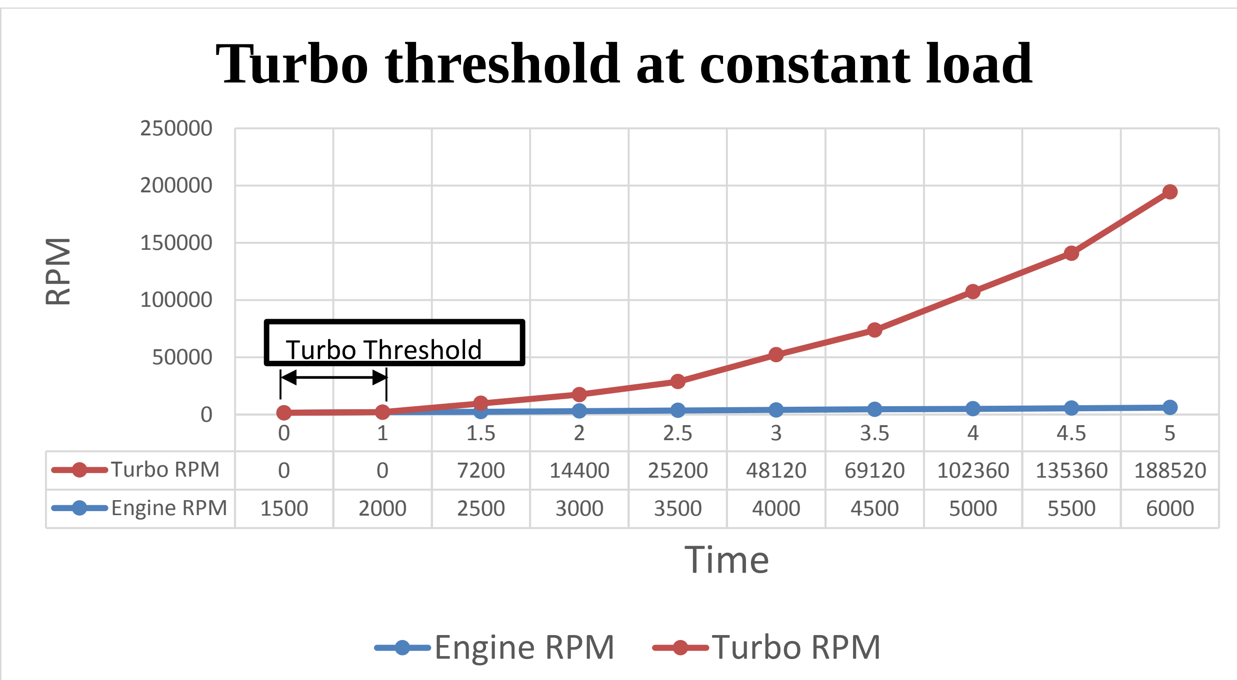


When we press the throttle, the Turbo does not respond at fist. Infact it respond after 2000 RPM because at RPM less than 2000, the concentration of exhaust gases is too low to run the turbine of the turbocharger. This is called threshold of the turbocharger. We can see in the following picture about threshold of the turbo at variable load.



	0	0.4	0.8	1.2	1.6	2	2.4	2.8	3.2	3.6	4	4.4	4.8	5.2
Turbo RPM	0	0	0	0	0	0	13080	38760	45960	52440	78720	93360	93720	1E+05
Engine RPM	0	420	840	1260	1680	2100	2520	2940	3360	3780	4200	4620	5040	5460

This is the threshold of the turbo at constant load.



	0	1	1.5	2	2.5	3	3.5	4	4.5	5
Turbo RPM	0	0	7200	14400	25200	48120	69120	102360	135360	188520
Engine RPM	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

As we press the throttle, the concentration of the exhaust gases will increase, and because of the concentration of the exhaust gases, the turbine and compressor blades of the turbocharger will move at higher RPM which will results in increase in the compressed gases into the intake manifold of the engine. When the compressed gases concentration will increase inside the cylinder of the engine, then it will boost more power without increasing the size of the cylinder. So we can say that when the pressure ratio of the turbocharger will increase, then the power boosted by the engine will also increase.

At the cold stat, when the engine RPM is less, the concentration of exhaust gases is also less, resulting in low turbine RPM because exhaust gases runs the turbine blades. Low RPM of turbine will result in less compressed air into the intake manifold of the engine so the power boosted at low RPM of the engine is negligible o vey less. And we can say that the response of the turbo is very less at low RPM.

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